Preliminary Results from a Laboratory Study of Charging Mechanisms in a Dusty Plasma

Catherine C. Venturini[†], James F. Spann*, and Richard H. Comfort[†]

*Space Sciences Laboratory, NASA Marshall Space Flight Center, MSFC, AL 35812 and [†]Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899

Abstract. A laboratory investigation has been developed to experimentally study the interaction of micron sized particles with plasmas and electromagnetic radiation. The intent is to investigate under what conditions particles of various compositions and sizes become charged, or discharged, while exposed to an electron beam. Primary emphasis in this report is on secondary emission of electrons. Preliminary results are presented.

INTRODUCTION

Dust particles are charged predominantly by absorption of charges due to collisions with thermal ions and electrons, photoionization due to incident UV radiation, and secondary electron emission due to collisions with energetic ions and electrons [1]. It is important to have a full understanding of the physics behind these mechanisms in order to understand observations and theory relating to dusty plasmas.

In light of the importance of studying charging mechanisms, a laboratory experiment has been developed that will specifically study secondary electron emission. This makes use of a laboratory technique known as electrodynamic suspension of particles [2,3,4], a technique that has been used in various fields including aerosols [5,6,7]. With this technique, a single, charged micron size particle is suspended using AC and DC electric fields and then subjected an electron beam. By controlled systematic use of this technique, a better understanding of the microphysics of a single charged particle in relation to different environments found in space and the laboratory can be achieved. This paper discusses the experimental setup and method, and provides an overview of preliminary results and future plans.

EXPERIMENTAL SETUP

The electrodynamic balance's design is based on an ideal geometry consisting of a bihyperboloidal electrode configuration where the inner surfaces are described by the equation

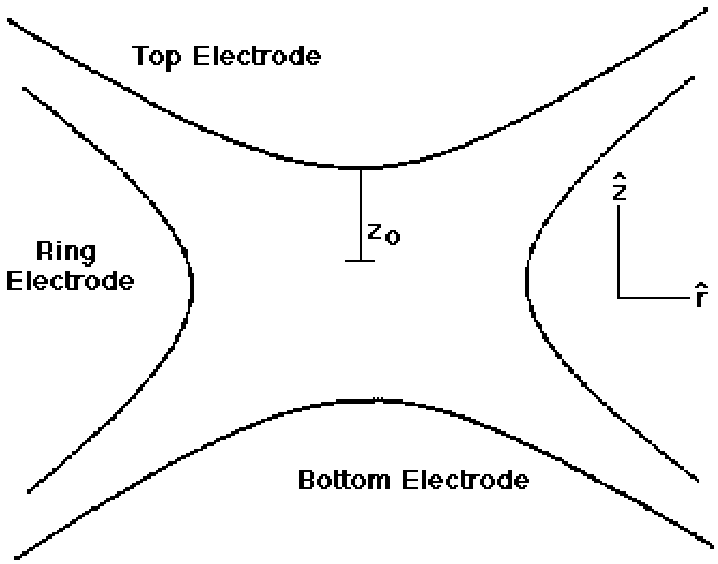

Figure 1. Cross-sectional view of electrodynamic balance with ideal geometry.

$$z^2 - \frac{r^2}{2} = \pm\frac{1}{z_o^2} , \tag{1}$$

where z is the vertical distance measured from the center of the cylindrical system, r is the radial component, and z_o is the distance from the center of the balance to the top/bottom electrode. The value $1/z_o^2$ will be positive for the two sheet hyperboloids which form the top and bottom of the balance and it will be negative for the one sheet hyperboloid forming the inner surface of the ring electrode (Figure 1) [2]. An AC voltage is applied to the ring electrode. Due to the time averaged electric field and the particle's inertia, a charged particle is confined to the point of lowest potential which is the geometric center of the balance. A DC voltage is applied between the top and bottom electrode to counter the effect of gravity and maintain the position of the particle at the center of the balance.

Based on the theory for ideal geometry, an electrodynamic balance has been constructed with a ring electrode made of stainless steel and top/bottom electrodes made of stainless steel wire mesh shaped into "hemispheres" [2]. The mesh hemispheres are welded to aluminum rings which fit into Noryl plastic rings that snap onto the top and bottom of the ring electrode. The balance's vertical distance is 39.62 mm and the radial distance is 41.28 mm with z_o = 4.65 mm, the distance from the center of the balance to the top or bottom electrode. The alternating potential has a range of 20-500 V_{ac} and a frequency, Ω, of 10 to 300 Hz. The DC voltage has a range of ± 0-25 Volts.

The balance is housed in a vacuum system made of stainless steel and glass. The glass is located around the balance for easy access to the particle and balance. All pieces of the vacuum chamber are attached using viton o-rings. A roughing pump and a small turbo pump is used to achieve a final pressure of 1.0 x 10^{-6} torr. A gate valve is located between the chamber where the balance is located and the vacuum pumps. A precision leak valve is placed in parallel with the gate valve.

In order to suspend a particle in the electrodynamic balance, the particle must have a charge. To charge a particle, a solution with soluble or insoluble particles is sealed in a tube with a plunger at one end and a small orifice with diameter of 15 microns at the other. A pressure pulse causes a stream of liquid droplets to be ejected. These droplets enter a static electric field produced by a potential difference between the orifice and charging plate. The liquid is then charged inductively and exits through a larger orifice. The water evaporates leaving the charged particle. Once the particle is charged, it is susceptible to the electric fields generated by the electrodynamic balance. With the correct parameters, the particle becomes “trapped” by the electric fields.

The particle is trapped, i.e. suspended in the balance, in air. With the main gate valve closed, the leak valve is slowly opened until both chambers on each side of the gate valve are under vacuum. The gate valve is then opened. This process takes about one hour.

Under vacuum the particle is subjected to an electron beam generated by a variable energy electron gun. The electrons are directed into the electrodynamic balance along its cylindrical axis through the top electrode. The electron energy can be varied from 5 eV to 3000 eV with a roughly constant circular spot size. For 50 eV, the gun can deliver a beam current of 1 μA into a 1 mm spot at a 2 cm working distance. A Faraday cup is located below the balance in order to record the total beam flux through the balance. It has an aperture of 4.75 mm. An electrometer is used with a special low noise coaxial cable to measure small currents.

A video camera is used to monitor the particle’s position for manual adjustment of the balance voltage. A computer is used to record the voltage values (Figure 2).

EXPERIMENTAL METHOD

From the geometry of the balance and the electric fields, we are able to measure the particle’s size. The size is determined by the results found from studying the solutions to the particle’s equations of motion in the balance. From these equations, the following parameters are used:

$$\kappa = \frac{18\eta}{\rho \Omega d^2}\ , \quad \text{and} \tag{2}$$

$$E = \frac{2qV_{ac}}{\Omega^2 m z_o{}^2}\ , \tag{3}$$

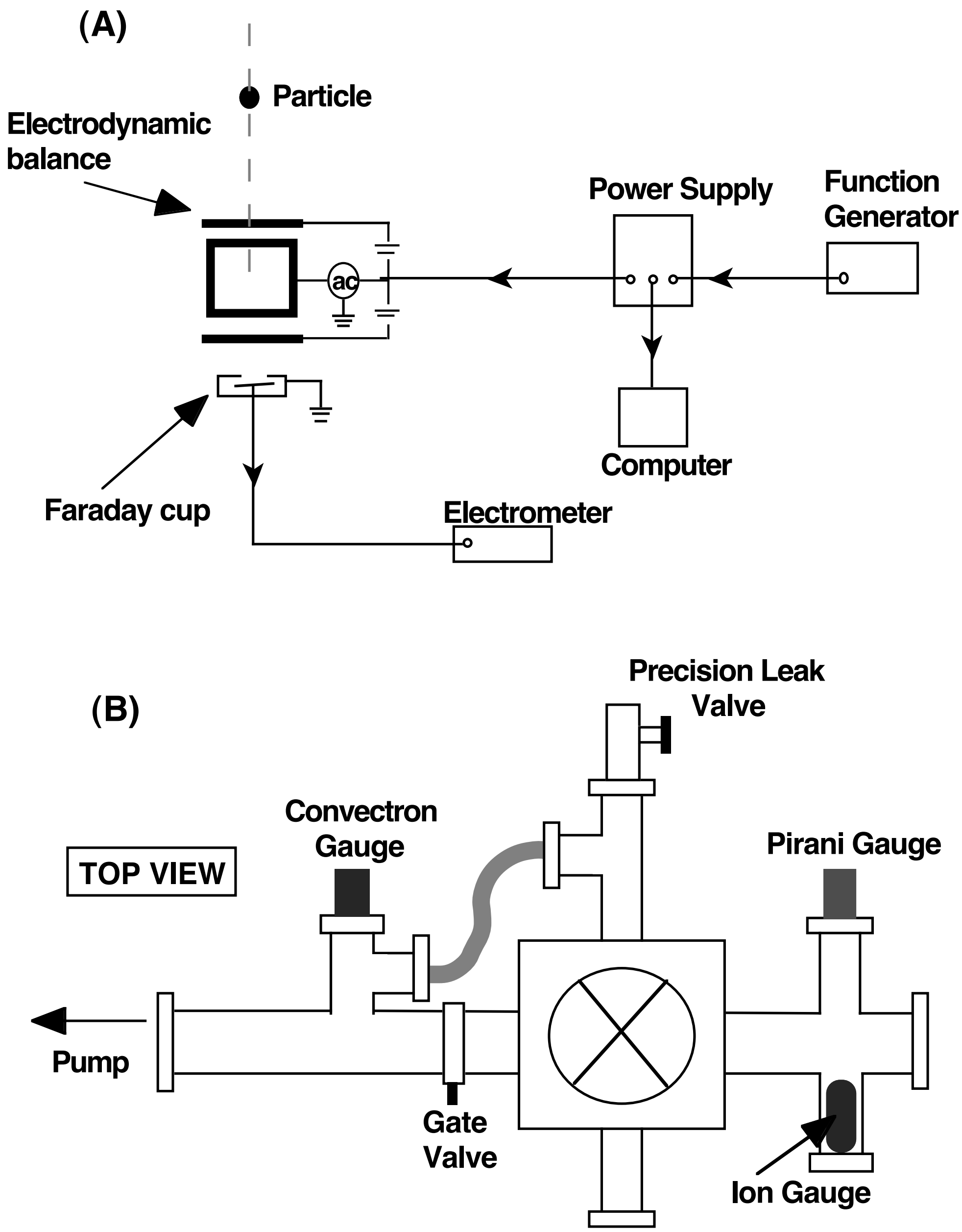

Figure 2. (A) Electrical Schematic. (B) Vacuum System.

where κ is the drag parameter, E is the electric field strength parameter, ρ is the particle's density, Ω is the frequency, q is the particle's charge, m is the particle's mass, η is the viscosity of the gas, $z_o = 4.65$ mm, and V_{ac} is the AC voltage.

In the laboratory, the electric field parameter, equation 3, is found by varying the voltage or frequency in air until the particle's motion becomes unstable. This is called the spring point measurement. The corresponding drag coefficient is found for the value of the electric field parameter from a plot of the solutions to the particle's equation of motion [2]. Knowing the drag coefficient, κ, equation (2) is evaluated for d, the diameter of the particle. The mass is determined by knowing the composition, and thus the density of the particle.

The charge-to-mass ratio is directly measured by adjusting the balance (DC) voltage so that the particle is located at the geometric center of the balance where there is a null point in the electric field. At the null point, the DC electric field counters the effect of gravity thus the sum of the forces in the vertical direction is equal to zero. Solving for the charge to mass ratio yields

$$\frac{q}{m} = \frac{g z_o}{c V_{dc}} , \tag{4}$$

where V_{dc} is the DC field voltage, g is the gravitational acceleration, $z_o = 4.65$ mm, and c is the geometrical constant. The constant c is required because the electrode geometry deviates from the ideal electrode geometry.

Once the charge and size of the particle are known, the mass of the particle can be calculated from equations (2), (3), and (4). Knowing the charge, one can also find the surface potential of the particle. The surface potential is found from the equation

$$\phi_s = \frac{q}{4\pi\varepsilon_o r} , \tag{5}$$

where q is the particle's charge, $\varepsilon_o = 8.85 \times 10^{-12}$ C^2/Nm^2, and r is the particle's radius, based on an assumed uniform surface distribution of charge on the particle. Frickel et al. [2], present a rigorous treatment of the particle's equations of motion.

PRELIMINARY RESULTS

The first goal of this investigation is to measure the secondary electron emission and consequently, the yield of a single dust grain. The approach described in the previous section is used. In order to accomplish this goal, the charge of the particle and it's rate of change must be determined. Therefore, the determination of the balance constant c in equation (3) is required. This was accomplished by finding an instability point under vacuum. Under vacuum, the electric field parameter has a maximum value of 0.908.

Knowing the value of E, then the constant c was found by using equations (3) and (4). Taking this measurement for two particles, c was calculated to be 1.24 ± 0.04.

With this value for the balance constant c, the measurement of the spring point for various NaCl particles indicated that the effective diameters ranged from 2.0 to 6.0 microns and masses from 1.0 x 10^{-10} to 9.0 x 10^{-12} grams. Based on equation (4), the initial charge on the particles was found to range from -5.0 x 10^{-16} to -1.0 x 10^{-14} Coulombs and potentials from -4.0 to -50.0 Volts. The number of electrons ranged from 2.0 x 10^{3} to 1.0 x 10^{5}.

The secondary electron emission or current can be determined by knowing that the net current to and from the particle is

$$I_{net} = \frac{dq}{dt} = I_e + I_{se} \ , \qquad (6)$$

where I_e is the primary electron current and I_{se} is the secondary electron current. Note that I_{se} includes other currents such as currents due to tunneling electrons and backscattering electrons since they cannot be distinguished in our particular experimental setup. We determine the secondary electron current from

$$I_{se} = \frac{dq}{dt} - I_e \ , \qquad (7)$$

where dq/dt is the change of the particle's charge as a function of time. Assuming the electron beam has a spatial Gaussian distribution, I_e is approximated by integrating the distribution over the cross sectional area of the particle. For low primary electron energies, the collisional cross section area is used. The collisional cross sectional area is described by

$$\sigma_c = \sigma_g \left(1 - \frac{2kq_p q_e}{(r_p) mv^2} \right) \ , \qquad (8)$$

where

$$\sigma_g = \pi (r_p)^2 \ ,$$

is the geometrical cross sectional area, k = 1.38 x 10^{-23} J/K, q_p and q_e are the charge of the particle and the electron respectively, r_p is the radius of the particle, m is the mass, and v is the velocity.

Preliminary results for an electron beam incident on a particle are shown in Figure 3. The particle was under constant exposure for 30 minutes to a 500 eV electron beam. The

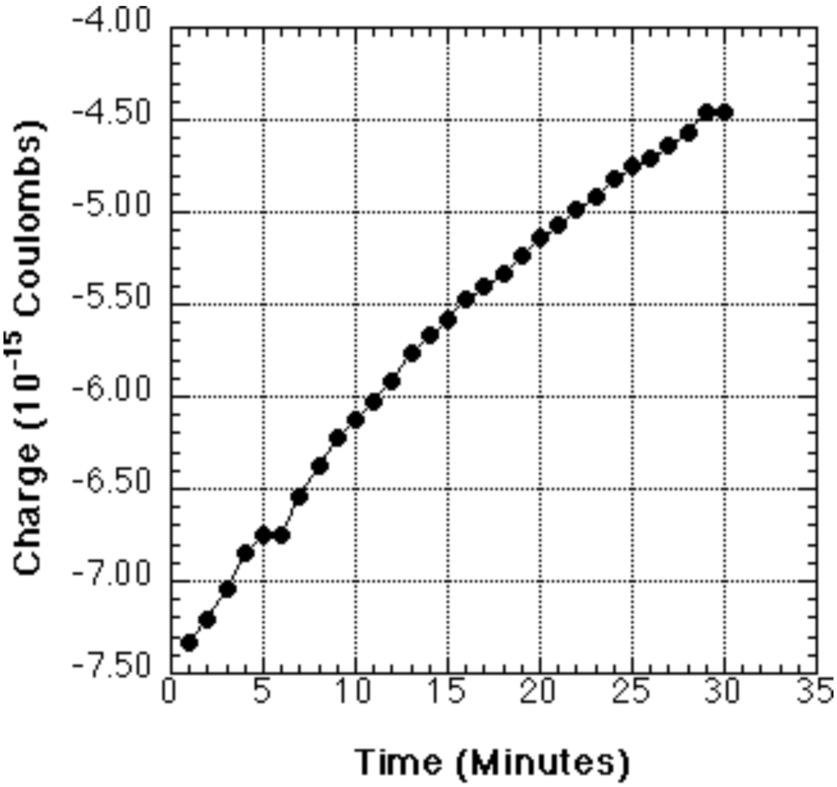

FIGURE 3. Plot of the particle's charge vs. time when subjected to electron beam with energy of 500 eV.

total electron beam current as measured with the Faraday cup was approximately 1.0-1.3 picoamps. The vacuum chamber's pressure was 1.4 x 10^{-5} torr, V_{ac} (V_{rms}) = 17.36 Volts, and the frequency was 100 Hz. Over the 30 minutes, the particle was steadily losing charge which suggests that the primary electrons were causing electrons to leave the particle thus producing a discharge current.

Assuming a linear variation approximation in Figure 3, the particle's discharge current was dq/dt = 1.68 x 10^{-6} pA. The primary electron current to the particle, I_e, was calculated to be -3.06 x 10^{-5} pA. Using equation (7), the secondary electron current, I_{se}, was calculated to be 3.23 x 10^{-5} pA. We expect this high value due to the fact that NaCl has a high secondary electron yield, which is the ratio of the secondary electron current to the primary electron current [8]. For this case, the secondary electron yield was 1.06.

FUTURE PLANS

Particles exposed to an electron gun to determine charge characteristics and secondary electron emission are continuing to be studied. This includes testing under different energy ranges. Besides using NaCl crystals, particles of various compositions including aluminum oxides, graphite, silicates, and polystyrene spheres will be tested. This includes studying both negatively charged and positively charged particles. In future experiments, particles below one micron will be studied.

A broad band spectrum deuterium lamp will be integrated into the system to study the effects of UV radiation on the particle. The deuterium lamp will be mounted to the vacuum chamber so that the UV is not absorbed by oxygen and wavelengths as short as 1150 angstroms will be incident on a particle.

ACKNOWLEDGMENTS

Funding for establishment of this laboratory was provided by the NASA Marshall Space Flight Center Center Director Discretionary Fund. C.C. Venturini is partially supported by the Alabama Space Grant Consortium NASA Training Grant NGT5 - 40018, and R.H. Comfort is partially supported by NASA / MSFC NCC8 - 65 at the University of Alabama in Huntsville.

REFERENCES

1. Goertz, C.K., *Rev. Geophys*., **27**, 271-292 (1989).
2. Frickel, R.H., Shaffeer, R.E., Stamatoff, J.B., *U.S. Army Armament Research and Development Command*, Technical Report ARCSL-TR-77041, (1978).
3. Wuerker, R.F., Shelton, H., and Langmuir, R.V., *J. App. Phys.*, **30**, 342-349 (1959).
4. Davis, E.J., and Ray, A.K., *J. Colloid Inerface Sci*., **75**, 566-576 (1980).
5. Spann, J.F., Maloney, D.J., Lawson, W.F., and Casleton, K.H., *Appl. Opt.*, **32**, 2152-2158 (1993).
6. Kurtz, C.A., and Richardson, C.B., *Chem. Phys. Lett*., **109**, 190 (1984).
7. Spann, J.F., and Richardson, C.B., *Atmos. Environ*., **19**, 819 (1985).
8. Kanaya, K., Ono, S., and Ishigaki, F., *J. Phys. D: Appl. Phys.*, **11**, 2425 (1978).